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## THE EFFECTS OF SOLAR PARTICLE EVENTS ON THE MIDDLE ATMOSPHERE

Charles H. Jackman and Anne R. Douglass<sup>1</sup>

Laboratory for Atmospheres  
Code 616  
NASA/Goddard Space Flight Center  
Greenbelt, MD 20771  
U. S. A.

Paul E. Meade

Department of Astrophysical, Planetary, and Atmospheric Sciences  
University of Colorado  
Boulder, CO 80309  
U. S. A.

## INTRODUCTION

Solar particle events (SPEs) have been investigated since the late 1960's for possible effects on the middle atmosphere. Solar protons from SPEs produce ionizations, dissociations, dissociative ionizations, and excitations in the middle atmosphere. Either directly or through a photochemical sequence both HO<sub>x</sub> (H, OH, HO<sub>2</sub>) and NO<sub>x</sub> (N, NO, NO<sub>2</sub>) are produced as well. These HO<sub>x</sub> and NO<sub>x</sub> constituents are important because they can lead to the destruction of ozone. Most of these investigations have been primarily focused on the effects of SPEs on ozone, however, a few have been related to the effects of SPEs on odd nitrogen (N, NO, NO<sub>2</sub>, NO<sub>3</sub>, N<sub>2</sub>O<sub>5</sub>, HNO<sub>3</sub>, HO<sub>2</sub>NO<sub>2</sub>, and ClONO<sub>2</sub>) constituents.

The SPEs are good tests for model validation because the large perturbations to the atmosphere associated with SPEs are confined to high latitudes, last only for days to months, and are easily distinguished in satellite data. This allows the comparison of measurements with a wide variety of models, ranging from simple point models to two-dimensional models.

Ozone depletions have been observed during and after nine separate SPEs over the past two solar cycles (HEATH et al. 1977; MCPETERS et al. 1981; THOMAS et al. 1983; SOLOMON et al. 1983; MCPETERS and JACKMAN, 1985). SPEs have also been observed to increase NO during one SPE (MCPETERS, 1986).

The production of HO<sub>x</sub> and NO<sub>x</sub> and their subsequent effects on ozone can also be computed using energy deposition and photochemical models. We discuss the effects of SPE-produced NO<sub>x</sub> species on the odd nitrogen (NO<sub>y</sub>) abundance of the middle atmosphere as well as the SPE-produced long-term effects on ozone. The influence of HO<sub>x</sub> species on ozone has been discussed in other papers (e.g., SOLOMON et al. 1981; JACKMAN and MCPETERS, 1985) and will not be repeated here.

ODD NITROGEN (NO<sub>y</sub>) VARIANCE DUE TO SPEs

The production of NO<sub>y</sub> species by SPEs has been predicted since the mid 1970's (CRUTZEN et al. 1975). Recently, a satellite measurement (MCPETERS, 1986) was made of the NO increase after a major SPE (July 1982). This measured NO increase was in good agreement with our predicted NO increase, computed

<sup>1</sup>Universities Space Research Association Resident Associate

assuming 1.25 nitrogen (N) atoms produced per ion pair (PORTER et al. 1976). The agreement between the predicted and measured NO increase has given us confidence in the reliability of the computations for NO<sub>y</sub> species' increase caused by SPEs.

A dataset of proton fluxes has become available from Thomas Armstrong and colleagues (University of Kansas) which allows for a daily computation of ion pair production and, subsequently, NO<sub>y</sub> production due to SPEs. The proton fluxes are given in integral form for energies greater than 10 MeV, 30 MeV, and 60 MeV. The data are available for the time period 1963 through 1985. We have used those data in a manner similar to that discussed in JACKMAN and MEADE (1988) and compute a daily ion pair production over the 23 year time period in a form suitable for inclusion in our model.

The ion pair production computed with the use of the daily average proton flux data of T. Armstrong compares favorably with the ion pair production computed using the hourly average proton flux data found in the Solar Geophysical Data publication for most SPEs. However for the August 1972 SPE, the ratio of the hourly computed ion pair production to the daily computed ion pair production ranges from about 3.7 in the stratosphere to near 1.0 in the mesosphere. We have normalized the daily to the hourly computed ion pair production for this one SPE only for two reasons: 1) the hourly computed ion pair production is believed to be more accurate than the daily computed ion pair production and 2) the August 1972 SPE is the most important SPE in the last two solar cycles for its effects on the middle atmosphere.

The ion pair production was input into our two-dimensional photochemical model (DOUGLASS et al. 1989) whose vertical range has been extended to be from the ground to about 90 km with about a 2 km grid spacing and from -85°S to 85°N with a 10° grid spacing. It was assumed that 1.25 N atoms are produced per ion pair in this model computation. The SPE production of N atoms was only input at geomagnetic latitudes above 60° (see JACKMAN and MEADE, 1988, for an explanation).

The two-dimensional model was run to an annual equilibrium condition in which the seasonal values of constituents repeat yearly. The model was then run for 23 years from 1963 through 1985 and investigated for changes. For all model runs in this investigation the ultraviolet flux was not allowed to vary with the solar cycle.

Figure 1a illustrates the variability of NO<sub>y</sub> at 1.7 mb (44 km) and 75°N over the 23 year period. Note that NO<sub>y</sub> can vary dramatically after an SPE, especially after the August 1972 SPE, but the NO<sub>y</sub> values generally return to their ambient levels 2 to 6 months after the event. The NO<sub>y</sub> seems to be affected only by those SPEs which have an ion pair production over about 100 ion pairs (cm<sup>-3</sup> sec<sup>-1</sup>). This is not a strict rule as the time of year and, therefore, the ambient NO<sub>y</sub> amount help determine the magnitude of the NO<sub>y</sub> change at a certain level (see JACKMAN and MEADE 1988 for further discussion). Some downflux of NO<sub>y</sub> from the SPE's mesospheric production of NO<sub>y</sub> is also associated with the SPEs and is important during certain seasons (late fall, winter, and early spring). This downflux can also influence the amount of NO<sub>y</sub> in the upper stratosphere.

Figure 1a, as well as our analysis of NO<sub>y</sub> at other altitudes and latitudes, indicate that the NO<sub>y</sub> produced by SPEs over solar cycle time periods does not build up, but can be important at high latitudes on seasonal time-scales. This result is not surprising given the small fraction of the annual odd nitrogen budget that was computed by JACKMAN et al. (1980) to result from SPEs. The majority of the annual production of odd nitrogen is a result of nitrous oxide oxidation and was recently computed (JACKMAN et al. 1987) to be  $2.7 \times 10^{34}$  NO molecules per year. The largest production of NO molecules from SPEs was in the

year 1972 at the level of  $6.4 \times 10^{33}$  NO molecules per year, only 24% of the nitrous oxide source. The production of NO molecules from SPEs in other major SPE-active years is typically half or less than that computed for 1972.

#### LONG-TERM OZONE VARIANCE DUE TO SPEs

Figure 1b illustrates the variability of ozone at 1.7 mb (44 km) and 75°N over the 23 year period. The ozone decreases are directly correlated with the NO<sub>y</sub> increases presented in Figure 1a.

The percentage change in modeled ozone as a result of the August 1972 SPE is given in Figure 2 at two latitudes. The latitudes in the Northern Hemisphere (N.H) at 75°N (Figure 2a) and 55°N (Figure 2b) indicate a larger ozone depletion at 75°N than at 55°N. Other latitudes investigated from our model results show a similar behavior with the larger ozone depletions being associated with the higher latitudes. This behavior was also observed in the UV ozone data (JACKMAN and MCPETERS, 1987). The magnitude of the depletion observed in the UV dataset was similar to that predicted by the model computation. For example, about a 15-25% maximum ozone depletion was observed between 70° and 80°N and about a 5-15% maximum ozone depletion was observed between 50° and 60°N.

Our model results at 55°S (not shown) indicates over a 20% ozone depletion, but the model at 55°N indicates a 5-10% depletion in the time period 20 to 60 days after the SPE, implying a large hemispheric difference in the level of ozone depletion. MAEDA and HEATH (1980/81) showed that the S.H. did experience a larger ozone loss than did the N.H. SPE-produced NO<sub>y</sub> in winter has a far greater effect on ambient NO<sub>y</sub> amounts and, therefore, on ozone levels than does SPE-produced NO<sub>y</sub> in summer (see JACKMAN and MEADE, 1988, for more discussion on SPE effects on NO<sub>y</sub> amounts).

#### DISCUSSION AND CONCLUSIONS

Model computations indicate fairly good agreement with ozone data for the SPE-induced ozone depletion caused by NO<sub>y</sub> species connected with the August 1972 SPE. Future studies should include a more detailed intercomparison of the ozone behavior with altitude, latitude, and time. It would also be useful to compare these detailed studies with another large SPE, perhaps one that occurs during the current solar active period. Since NO<sub>y</sub> constituents are responsible for over 70% of the ozone loss in the stratosphere (JACKMAN et al. 1986), it is useful to validate the NO<sub>y</sub> photochemistry which is used in atmospheric models to predict ozone amounts.

Our model computations indicate that NO<sub>y</sub> will not be substantially changed over a solar cycle by SPEs. The changes are mainly at high latitudes and are on time scales of several months, after which the NO<sub>y</sub> drifts back to its ambient levels.

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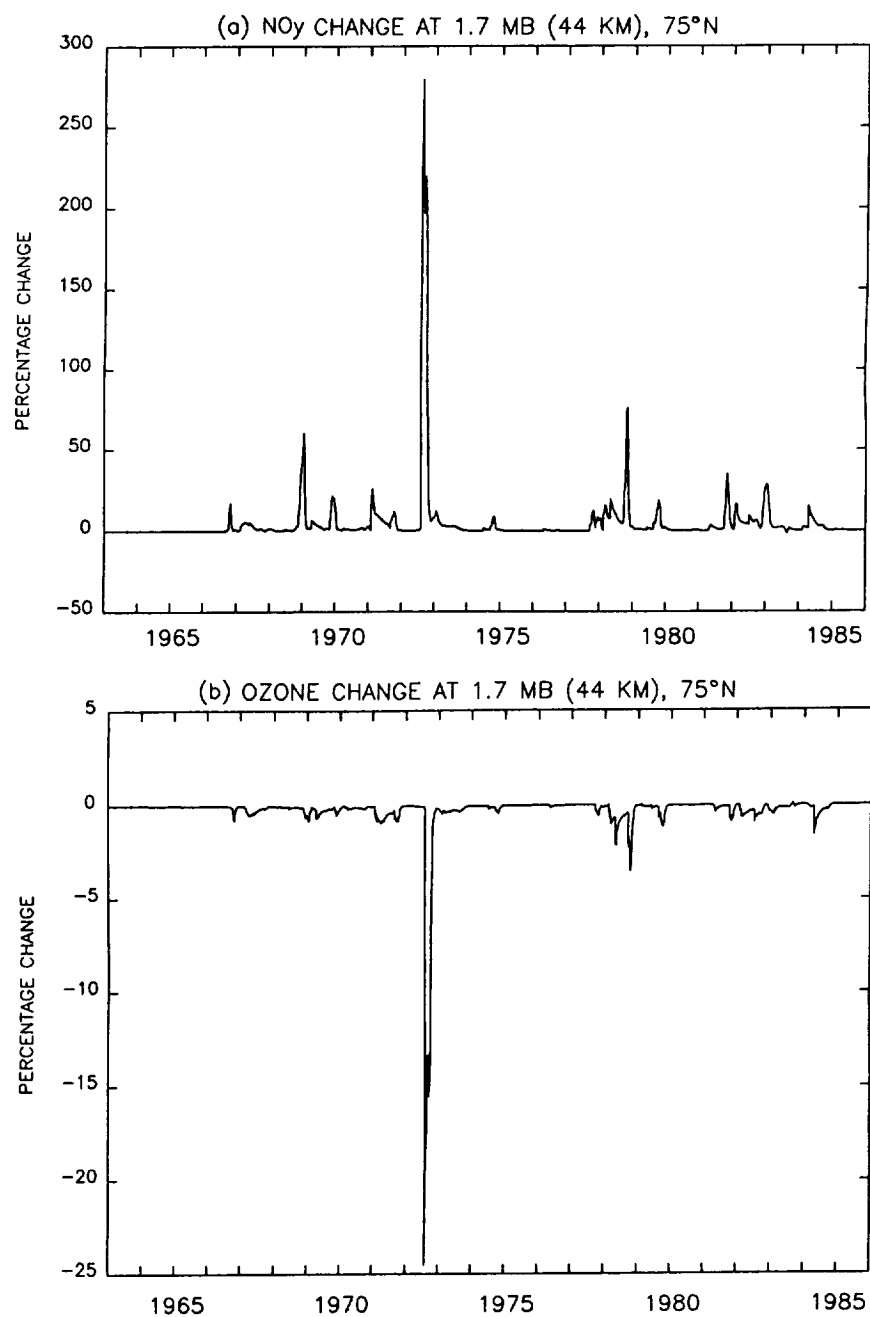


Figure 1. (a) Model predicted NO<sub>y</sub> percentage change at 1.7 mb (44 km) and 75°N. (b) Model predicted ozone percentage change at 1.7 mb (44 km) and 75°N.

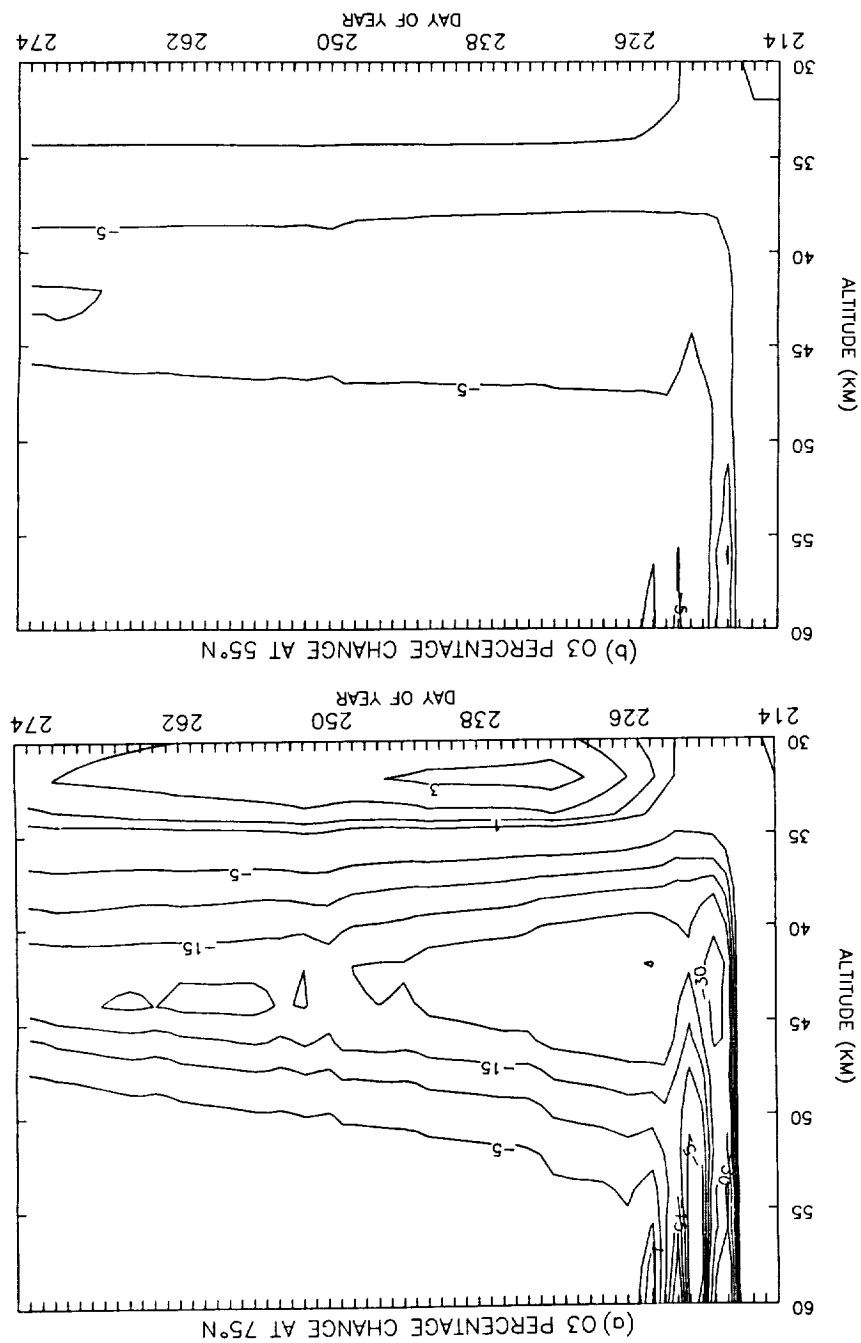


Figure 2. Model predicted ozone percentage change as a function of day of year in 1972 for (a) 75°N and (b) 55°N. The ozone change is a result of the August 1972 SFR and is given at the contour levels of -40, -30, -20, -15, -10, -5, 0, +1, +2, and +3%.